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Wind energy: Increasing deployment, rising environmental concerns

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ABSTRACT

Of all the renewable energy sources (RESs)–except direct solar heat and light–wind energy is believed to have the least adverse environmental impacts. It is also one of the RES which has become economically affordable much before several other RESs have. As a result, next to biomass (and excluding large hydro), wind energy is the RES being most extensively tapped by the world at present. Despite carrying the drawback of intermittency, wind energy has found favor due to its perceived twin virtues of relatively lesser production cost and environment-friendliness.

But with increasing use of turbines for harnessing wind energy, the adverse environmental impacts of this RES are increasingly coming to light. The present paper summarizes the current understanding of these impacts and assesses the challenges they are posing. One among the major hurdles has been the NYMBI (not in my backyard) syndrome due to which there is increasing emphasis on installing windfarms several kilometers offshore. But such moves have serious implications for marine life which is already under great stress due to impacts of overfishing, marine pollution, global warming, ozone hole and ocean acidification. Evidence is also emerging that the adverse impacts of wind power plants on wildlife, especially birds and bats, are likely to be much greater than is reflected in the hitherto reported figures of individuals killed per turbine. Likewise recent findings on the impact of noise and flicker generated by the wind turbines indicate that these can have traumatic impacts on individuals who have certain predispositions. But the greatest of emerging concerns is the likely impact of large wind farms on the weather, and possibly the climate. The prospects of wind energy are discussed in the backdrop of these and other rising environmental concerns.

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1. Introduction

1.1. The affordability and the perceived cleanness of wind energy

Wind energy is popularly perceived as one of the cleanest sources of energy. It is also the first of the renewable energy sources that has become ‘affordable’—i.e. become capable of generating electricity at rates comparable with conventional energy sources (with or without subsidies).

Due to these twin advantages, wind energy is the most utilized of all renewable energy sources (RESs) for electricity generation today (if large hydropower is excluded from the consideration, which it generally is). Until 2007 Germany was leading the world as the biggest producer of wind-based power, followed by Spain and India (Fig. 1). In 2008 USA surged ahead, but only to be overtaken by China in 2010. Within Asia, India was the leader till 2007. But since then China has not just overtaken India but has zoomed so far ahead that it is now generating more than 3 times as much power from wind energy as India. With plans to start producing another 200 GW soon, China is expected to remain the world leader in the foreseeable future. India is now the fifth biggest producer of wind-based power in the world, with an installed capacity of 17.4 GW at present.

But these figures are impressive only when we compare wind energy with other RESs. If we look at the overall global energy scenario the perspective is very different. Wind energy meets a mere 0.2% to the total global energy demand and just 1.8% of all the world's electricity is being generated by wind energy [78,113]. This picture will change soon because of strong initiatives across the world to enhance the utilization of wind power for electricity generation. The main impetus for this comes from the urgency to control global warming by replacing coal-based and other fossil fuel-based energy generation with RESs [8]. Wind energy being, at present, the most affordable and apparently most clean of all other known RESs, is being expected to lead the shift from fossil fuels to RES.

1.2. The increasing deployment of wind energy

The Inter-governmental Panel on Climate Change (IPCC) in its recent report [47] has hoped that more than 20% of the world's electricity demand would be met by wind energy by the year 2050. The USA aims to reach this goal much earlier—by 2030 [241]. The “20-20-20” target set by the European Union [29] which aims at reducing greenhouse gases by 20%, reduces primary energy use by 20%, and enhances the contribution of renewable sources to meet 20% of the EU's energy demand by the year 2020, also aims to rely heavily on wind energy for meeting the first and the third of its targets [27]. Unless China surrenders its position as the world's biggest producer of wind-based electricity, it would also be soon meeting 20% or more of its power needs with wind energy. The Indian government has equally ambitious plans to enhance its wind power generation capacity [174,220]. Other countries are bracing to follow suit [211,218,236].

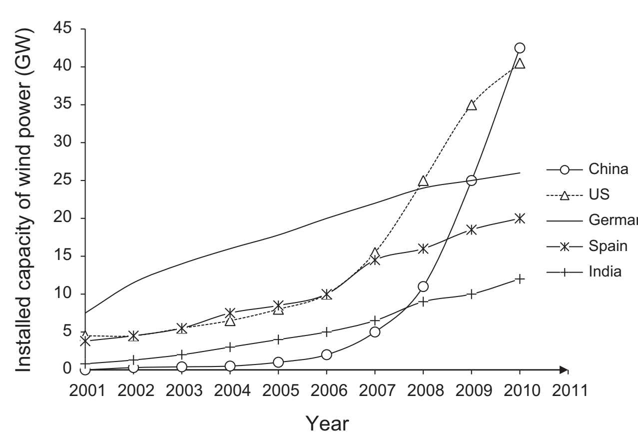

Fig. 1. Wind power generation by the world's top five wind energy harvesters (adapted from Ref. [151]).

At the present estimates the global electricity demand will be 8.5 TW by 2050 (Fig. 2). If 20% of it is to be met with wind energy this means that by 2050 the world needs to produce 50 times more power from wind energy than it is doing today! In other words in every coming year the world must add more capacity for wind electricity generation than the sum-total of the wind power capacity it has developed so far. The growth has to be still more brisk in the USA and the EU in order to meet their more ambitious targets. Seen in another light, Fig. 2 reveals that even as electricity demand would approximately double from its present value by 2050, to meet 20% of this demand from wind energy, the capacity of the latter must increase 50 times by 2050.

Will such a large-scale deployment of wind energy be free from adverse environmental impacts? Or will it cause only minor impacts that would be easy to reverse or manage? The world is planning to make equally significant shifts to other renewable energy sources in its attempt to replace fossil fuels by renewables [3–8]. If the solar thermal, solar photovoltaic, biomass, geothermal, small hydro, wave, tide, and ocean thermal energy systems are all developed to the extent the world is hoping to, will the impacts be still minor?

This paper aims to address these questions.

1.3. Changing perception

Till the beginning of the 1980s there were very few wind turbines in the world. At that time wind energy was thought to be totally 'clean' and totally free from any adverse environmental impact [1,2]. The popular perception was that all one would need would be to install a wind turbine on the roof of one's house and that would ensure supply of clean energy for the house throughout the year.

About 22 years have since passed. By now several wind farms have been installed in different parts of the world. The wind energy based power generation which was just 2.4 GW in 1990 has grown 122 times by now to about 295 GW (Fig. 3).

Even though, as said earlier, by now just 0.2% of global energy demand is being met by wind energy, those who are associated with wind energy no longer call it a "totally clean source of energy with no adverse impacts". This is because several adverse impacts have come to the fore now, and more are emerging as ever larger wind turbines are being installed and ever bigger wind farms are being set up in different parts of the world.

An increase in the use of wind energy from generating a couple of GW to a few hundred GW has brought a charge in perception from it being 'non-polluting' to 'less-polluting'. It appears

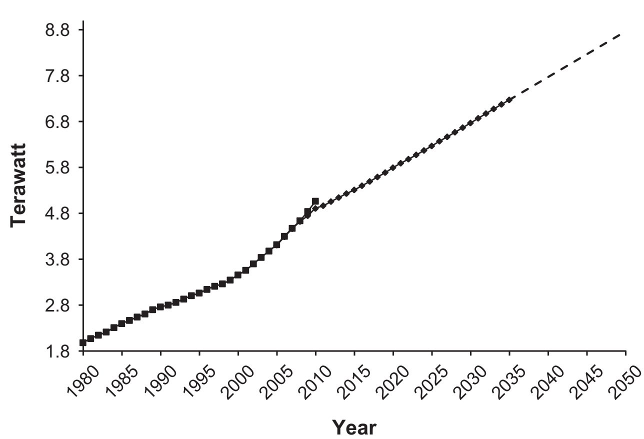

Fig. 2. Global electricity generation–past and future. The curve for the years 1980–2010 provides historic data for the electricity installed in that period. The curve for the years 2010–2035 is based on the forecast of the United States Energy Information Administration [242]. The curve spanning 2035–2050 is a linear extrapolation of the USEIA forecast.

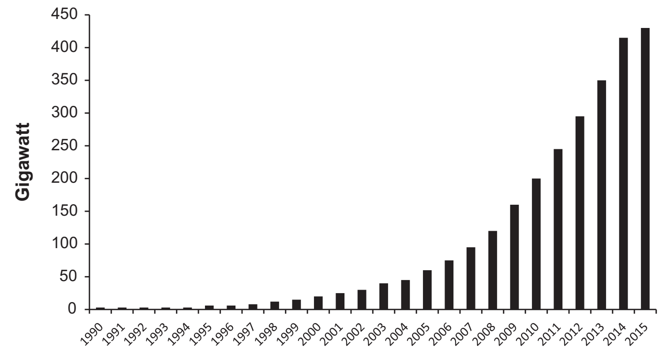

Fig. 3. Growth in the global wind power installed capacity upto 2012 and forecasts for 2013–2015.

reasonable to draw from this wisdom of hindsight and forecast the situation when several thousand GW of power will be generated with wind energy.

2. A brief history of wind energy

2.1. Use of wind energy down the ages

It is safe to assume that the use of natural breeze to dry and cool the body, with or without the aid of passive solar energy (sunlight), was the earliest form of the use of wind energy by the humankind. Much later, when humankind had learnt to make boats it began using wind energy for transportation on water by harnessing the wind's kinetic energy with the help of sails. Indeed for several thousand years wind was used as a source of transportation energy in this manner [9]; the speed and the direction of the boats and the ships were controlled by the number and the orientation of their sails.

Some 3000 years ago humankind invented windmills [105,116]. The earliest recorded windmills had vertical-axis and were used in the Afghan highlands to grind grain since the seventh century BC. The first windmills had sails similar to those on a boat. The sails were fixed to a vertical-axis wheel that turned horizontally. Those windmills were built inside towers with slots through which wind blew on the sails, moving the wheel. The grindstones attached to the wheel moved as the wheel moved, enabling the grinding of the grain [18]. The horizontal-axis windmills came much later; their first details are found in historical documents from Persia, Tibet and China at about 1000 AD [134]. This windmill type which is familiar to us, and which is the fore-runner of the present day wind turbines, has a horizontal shaft and blades (or sails) revolving in the vertical plane. From Persia and the Middle-East, the horizontal-axis windmill spread across the Mediterranean countries and central Europe. The first such windmill appeared in England around 1150 [11]. France, Belgium, Germany, Denmark, and other European countries followed suit in building windmills. From then till the 19th century, windmill technology was constantly improved across the world. By 1800, about 20,000 windmills were in operation in France. In the Netherlands, 90% of the power used in industry was from wind energy. These windmills were, typically, 30 m tall and used rotors of about 25 m diameter. The emergence of fossil fuels caused a decline but even in 1904 wind energy provided 11% of the Dutch industry energy requirements and Germany had more than 18,000 units [11].

In the initial decades of the 20th century, windmills slowly started to disappear in Europe, but they began to show up in North America, as the European immigrants installed small windmills for pumping water for livestock, especially in areas which, in those days, were not supported by the electricity grid. Those windmills,

also known as American Windmills, operated fully self-regulated, hence they could be left unattended. The self-regulating mechanism pointed the rotor windward during high wind speeds [105,116,207]. The European style windmills usually had to be turned out of the wind or the sailing blades had to be rolled-up during extreme wind speeds, to avoid damage to the windmill. The popularity of windmills in the USA reached its peak between 1920 and 1930 with about 600,000 units installed.

2.2. Electricity from wind energy

During the 1880s a British inventor James Blyth and an American inventor Charles Brush, working independently and without the knowledge of each other, made the first demonstrations of generating electricity from windmills. Perhaps the British inventor predated his American counterpart by a few months [201], generating electricity from a windmill in July 1887 [38]. Blyth used the electricity to charge batteries for his household lighting, but also offered surplus electricity to the people of Marykirk for lighting the main street. Interestingly, the villagers turned down the offer, as they thought electricity to be the work of the devil [15,161]! Blyth did manage to install a wind machine to supply emergency power to the local Lunatic Asylum, Infirmary & Dispensary.

In 1891, Poul LaCour built a wind turbine for generating electricity in Denmark. Danish engineers improved the technology during World Wars I and II and used the technology to overcome energy shortages during the wars. The wind turbines built by the Danish company F.L. Smidth in 1941–1942 were the first to use modern airfoils, based on the advancing knowledge of aerodynamics at that time. During the same years Palmer Putnam built a giant wind turbine, which was much larger than the other wind turbines of that era, for the American company Morgan Smith. It had a diameter of 53 m. Not only was the size of this machine significantly different from the Danish windmills, but so was the design. While the Danish windmill was based on an upwind rotor with stall regulation, operating at slow speed, Putnam's windmill had a downwind rotor with a variable pitch regulation [11].

Despite these and other advances which led to increasingly efficient turbines, the interest in large-scale wind power generation declined after World War II as the world preferred the more convenient, efficient, and reliable fossil fuels for all its energy needs. Only small-scale wind turbines, for remote area power systems or for battery charging, remained in use. The 'oil shocks' of 1973 and 1979 revived interest in renewable energy sources, including wind energy, but the enthusiasm slacked with the gradual easing of the oil crisis through the late 1980s to the end of the 20th century. Then, as global warming became an increasingly accepted reality in the early years of the present century there has been a very strong revival of interest in wind energy. The revival seems to be for good this time [9].

3. Environmental impacts of inland wind farms

The drone of a moving wind turbine, especially when it seemed to pierce the silence of a night, was the first adverse environmental impact of wind energy that had surfaced. The next to emerge and gain prominence was the visual impact—perception of wind turbines adversely effecting the scenery [33,106,233]. The few murmurs of protest that were heard *vis a vis* noise-related disturbance were joined with louder protests and citizen's movements against siting of wind parks in one or the other region on the grounds that it tarnished the otherwise esthetically pleasing looks of a place. The third major impact to draw attention has been harm to birds and bats which get maimed or killed in flight when they run into wind turbines [70,71,110]. Interference with television transmissions and distrution caused by flickering shadows of moving turbines have been other objectionable consequences of wind power generation. Now the most shocking of the adverse impacts is coming in view—on the climate [254,267]. It was being feared since 2004 on the basis of theoretical studies but now concrete evidence is emerging that large wind farms can influence local weather but are also likely to influence the climate and can bring in significant changes in it.

What is the nature of each of these impacts and how serious each has been? To what extent attempts to mitigate them have succeeded or have the potential to succeed? What shape each of these aspects is likely to take as the world moves into the future with the expectation to generate 20% of its power from winds in the coming years?

3.1. Visual impact

3.1.1. The NIMBY syndrome and the efforts to fathom it

There has been a strange dichotomy associated with public acceptance of wind energy [178]. An overwhelmingly large majority perceives wind energy as highly benign and desirable ([86,118,177,231]) but most who favor wind energy do not favor wind turbines to be located near them [69,269]. Many prefer not to have wind turbines wherever they happen to go often enough. As wind turbines are made larger and larger (Fig. 4) to make them more economical and to reduce their carbon footprint per unit energy generated [48], their dominance on landscapes and the extent of their visibility is also proportionately

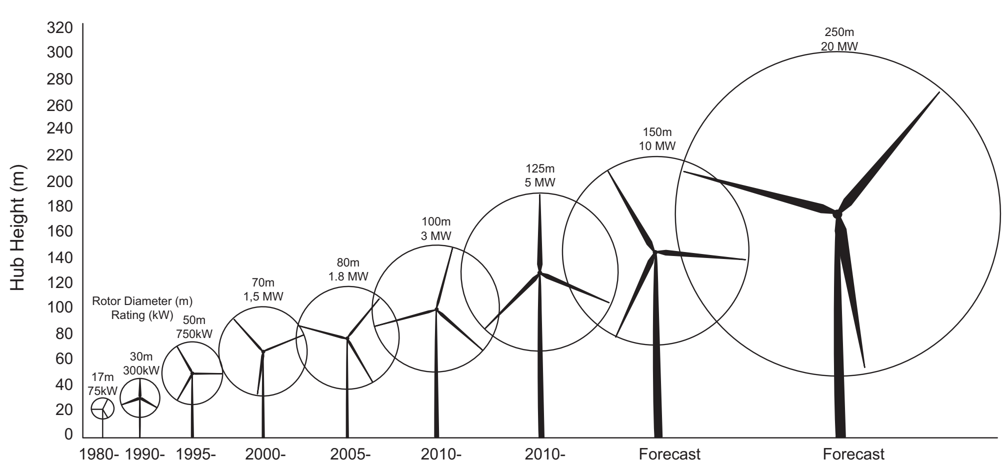

Fig. 4. Growth in size of commercial wind turbines (adapted from Ref. [113]).

increasing. With it is increasing public resistance to the installation of wind turbines within viewing distance [97,142,143,156,269].

Enormous research has been done, and is continuing to be done, to break the prevalence of this NIMBY (not in my back yard) syndrome. The research has aimed at finding the esthetic, socio-economic, political, and behavioral reasons behind the NIMBY syndrome with the aim to find ways around it. An early study by Bergsjo et al. [34] identified four scales of visual influence of a wind turbine:

- a sweep zone, defined by the radius of the rotor blade;
- a visual intrusion zone in which a unit is perceived as visually intrusive; it is about 5 times the total height of the unit;
- a visual dominance zone bounded by the maximum distance at which the turbine tower dominates the field of vision; it is about 10 times the height and
- a visibility zone inside which the unit can be seen easily but is perceived as belonging to the distant landscape (extends to about 400 times the height of the unit).

Bergsjo et al. [34] further observed that when many turbines are grouped or repeated as elements in the landscape, these zones become even larger. It is this high level of visibility and the sense of intrusion on the surrounding landscape that invokes strong opposition for wind parks.

The other factor that distinguishes wind turbines' visual impact is their stark visual expression of function: the turbines provide immediate, direct, evidence to the public whether they are operating or not. When arrays of wind turbines are all turning, the viewer receives an immediate evidence of their usefulness. On the contrary when significant numbers of turbines are idle it generates feelings of belied expectation [233].

Various other types of symbolic or connotative meanings are attached by different individuals or communities to wind turbines existing in different situations and in different contexts. The nature of such reactions differs from culture to culture, as also within a community if some individuals are benefitted by the turbines while some others are not. Attitudes also differ; beholders may view a wind farm positively if they consider the development to be appropriate, efficient, safe and natural (in the production of energy), progressive and a sign of the future. On the other hand, for subjects with negative attitudes wind turbines represent visual conspicuousness, clutter and unattractiveness. In a study by Ferber [83], in which reactions to different photographic simulations were obtained, each visual showing a different windmill in the same landscape setting, only a traditional Dutch windmill was considered to be a positive addition to the landscape by the majority of the subjects. All other modern turbines were judged to have neutral or negative impact. One simulation showing a row of seven modern wind turbines was rated only slightly less negatively than an ordinary powerline.

3.1.2. Tools to determine the degree of acceptability of wind turbines

Visualization tools to assess the degree of acceptability of different turbine sizes, turbine densities, turbine arrays, and turbine color schemes in a given location have been developed. For example Miller et al. [172] have formulated an interactive visualization procedure for illustrating the visual effect of turbines from different positions and also moving them about interactively in virtual space to help create patterns of turbine arrays that may be acceptable to the viewer. Lange and Hehl-Lange [144] have also used visualization as a tool to help allay community concerns and arrive at preferred design options. Álvarez-Farizo and Hanley [16] have used image manipulation and conjoint analysis in an attempt to quantify the social costs of wind farm development. Based on simple distance functions, without visibility assessment, Baban and Parry [24] have used GIS to map site suitability by integrating wind resource utilization with avoidance of populated or visually sensitive areas.

It has been understood since long that the rate of impact decline is affected by factors such as the nature of the background, the local landscape and the landscape between the viewer and the turbines. These are particularly relevant for on-shore turbines that occur in a variety of visual contexts and possess a variety of visual absorption capacities [17]. Off-shore facilities are much less influenced by these considerations, yet off-shore proposals are also meeting with objections on visual grounds [37].

It has been argued [36,219] that contrast between the turbines and their background of sky is important and needs to be quantified. But atmospheric patterns are ephemeral and the sky-turbine contrast can change within weeks or days, sometimes within hours. Nevertheless in locations such as the ones which have a large number of clear days or a large number of foggy days, with relatively long-lasting weather patterns, color schemes can be devised which can reduce turbine–skyline contrast for as longer duration in an annual cycle as possible.

Attempts have also been made at quantifying and ranking visual impact, which include the so-called Quechee Test [184] and the Spanish method [111]; other multi-criteria impact evaluation frameworks [91,237]; perceptions modeling [142]; and quantifying the intensity of sensory perception [114].

The discussion in the preceding paras indicate that sincere efforts have been done since over 35 years to minimize or eliminate public opposition to wind turbines on account of the latter's visual impact. But all these efforts have been stymied by the unsurmountable challenge one faces when trying to quantify esthetics. It is an exercise no more easy than grading *objects d' art* on scales of excellence or developing a model which can prove whether Da Vinci was a greater painter or Picasso. The classical adage *beauty lies in the eyes of the beholder* is operative with the added dimension of presence or absence of self-interest. If a thermal power plant can be dismantled and a wind farm put in its place which could generate equivalent amounts of power, such wind farms will have near-universal acceptability. Wind farms on degraded or denuded lands, well away from residential localities, will also be generally welcome. But situations like this which *also* possess high wind energy potential are rare to find. In other situations the acceptability of wind turbines is more equivocal, giving rise to the challenge of finding the trade-off.

3.1.3. A few rules-of-thumb

Despite the impossibility of quantifying esthetics, a few broad aspects that contribute to the acceptability or otherwise of wind farms have been identified:

Perception of usefulness: as said earlier, if a wind farm replaces a more disagreeable source of power, it will have a high degree of acceptability. Even otherwise a wind farm which is functional for large parts of an year, delivering power when it is needed the most, is likely to be popular. On the contrary, when the majority of the wind turbines in a wind farm are standing still (due to lack of wind) at times like on peak summer or winter when electric power is needed the most, it generates the negative perception of a ‘dead weight’, a kind of trickery.

Perception of intrusiveness: depending on the nature of terrain and local geography different perspectives of size can result from wind farms of identical turbine size, number, and specing. For example a wind park installed on vast flat lands would appear smaller than a farm of identical size located at the top of a hill in a small island. The latter will appear more intrusive and overpowering than the former. In general, the visual impact of a wind farm on a landscape is much greater in narrow and closed

formations than in open areas. In the like manner a wind farm near areas of tourist attraction, especially ones related to heritage, would appear particularly intrusive. Likewise installation of a wind farm in the neighborhood of areas with remarkable natural beauty is deeply resented.

The visual impact of a wind turbine is dampened as one goes away from it [37]. The impact remains significant upto distances which are within 10 times the wind tower's height. Inside an area of this radius, the wind turbines begin to dominate the landscape. In clear weather, a turbine may be visible at distances upto to 400 times its tower height. This means that a wind turbine with a tower of 50 m height may be visible at distances of 20 km.

Perception tainted by self-interest or a lack of it: those who derive economic benefit from a wind power project have a very high degree of acceptability for it in contrast to those who are not benefitted.

Apart from the aspect of visual integration with the landscape, a color scheme associated with a wind farm can enhance or diminish its looks. It is generally accepted that the use of tubular towers rather than lattice ones improves the presentability of a wind farm. Another contributing factor is the visual symmetry and the grace of form associated with each turbine. How the color of the turbine's blades and the tower blends with the background can also influence the visual appeal (or the lack of it) of a wind park [156,237].

3.1.4. Public preferences versus economics of scale

Several studies have brought out that smaller wind farms are more positively perceived in comparison with larger-scale developments [69]. Lee et al. [150] refer to a 'favourability gradient' in noting a negative linear relationship between wind farm size and public support. The support was highest for wind farms in the UK with less than eight turbines. This finding has been replicated in several other countries. Research in Denmark [62] reported that clusters of two to eight turbines received more public support than both scattered single turbines and larger arrays. This finding was consistent across gender and age groups in this large-scale, representative Danish sample. From the Netherlands, Wolsink [266] has reported that wind farm developments were less highly supported than stand-alone turbines in a review of 11 empirical studies. In Ireland, too, [230] there is a preference for smaller, clustered groups of turbines over larger-scale installations; smaller numbers of large turbines are considered preferable to larger numbers of smaller turbines.

The public preferences reflected above are in direct conflict with the interest of wind power developers for whom larger-sized turbines and bigger wind farms represent increasing benefit due to increasingly favorable economics of scale. Large-sized turbines and bigger wind farms are also required to extract maximum benefit from favorable locations which, otherwise, will be used to much below their potential.

3.1.5. The portents

Other public preference revealed by more than one surveys is for the 3-blade turbines over 2-blade ones as the former appear more symmetrical [240].

From the foregoing it is clear that visual impact of wind farms will become an increasingly pressing issue as their number increases. With competition for uninhabited spaces increasing due to the needs of other space-consuming renewable–based power generation systems such as solar thermal/solar photovoltaic and small hydropower, it will become increasingly difficult to find sites for wind forms that would not jeopardize the few remaining areas of wilderness, or encroach upon open spaces meant for recreation. The NIMBY syndrome would be increasingly operative more so because installation of wind turbines near areas of real estate value lower the latter's worth. Offshore wind farms, discussed in Section 4 of this paper, suffer less from NIMBY but are not entirely free from it even as they suffer from other special problems of their own.

3.2. Noise

3.2.1. Nature and intensity of noise generated by wind turbines

Unlike the issues of esthetics as shaped by the conscious and the sub-conscious mind, which are associated with the visual aspects of wind turbines, noise is quantifiable on the decibels scale. Even then, a great deal of subjectivity is encountered when determining whether a noise is agreeable or disagreeable. Subjectivity is also associated with determining the degree of annoyance a noise may cause.

If one has to face it only for a short duration, the noise emanating from a wind turbine is not much of a distraction. But if the slapping/whistling/swishing sound of the whirling turbines has to be endured day in and day out, it can be annoying. The persistence of the noise is as big a contributing factor to its unpleasantness as its fluctuating levels or its nature. The awareness of the noise gets muted by the usual day-time din but it becomes very noticeable during the nights. If the nature of the locality is such that the background sounds generated by traffic and other forms of community noise are not strong, the sound of the turbines can become poignant.

Two forms of noise emanate from wind turbines—mechanical and aerodynamic. The mechanical noise is caused by the moving electromechanical parts of the machine. Its main sources are the machine's gear box, the electrical generator and the main shaft's bearings. The aerodynamic noise consists of the rotation noise and the turbulence noise [182]. Both are functions of the blade's aerodynamic design and the wind velocity.

The rotation noise increases with the rotor's diameter, the reduction of the blades' number, the blades' angular velocity, and the blades' aerodynamic load (increase of the captured wind energy).

The turbulence noise is produced by the vortex at the edge (tip) of the blades and the turbulence behind the rotor leading to an increase in the sound pressure levels (SPLs) with the tip speed. It goes down with the reduction of the blades' angular velocity; in other words greater the power being extracted by a turbine, more noisy it is.

Mechanical noise is in frequencies below 1000 Hz and may contain discrete tone components, which are known to be more annoying than noise without tones. But it is the aerodynamic noise which is the dominant component of wind turbine noise today, as manufacturers have been able to reduce the mechanical noise to a level below the aerodynamic noise. The latter will become even more dominant as the size of wind turbines increases, because mechanical noise does not increase with the dimensions of turbine as rapidly as aerodynamic noise does [191].

The sound power levels of a present day wind turbine are in the 98–104 dB(A) range at a wind speed of 8 m/s, which result in an exposure of about 33–40 dB(A) for a person living 500 m away. Studies by Pederson and coworkers [27,115,192,194–196] and Persson and Öhrström [193] have shown that SPLs of this low magnitude are not a source of annoyance when they come from other sources of community noise, such as road traffic and aircraft. But the sound from the wind turbine is amplitude modulated by the pace of the rotor blades, which gives a rhythmical swishing tone. Such sounds are more distracting than an even sound [270] and are, by-and-large, more negatively perceived.

Suitable locations for the installation of wind turbines are often in regions far away from urban clusters. In such rural settings, when

other forms of background community noise are not high, turbine-based noise easily stands out, contributing to its undesirability.

3.2.2. Factors which lead to annoyance or acceptability

As in the case of visual impacts, a good deal of research has been done to identify the social, economic, psychological and esthetic attitudes which make a person react accomodatively or unfavorably to wind turbine noise. Some broad pointers that have emerged are

(a) the chances of a turbine's noise being perceived as a source of annoyance increase if the turbine is visible to the recipient of the noise;
(b) those who economically benefit from the presence of turbines are less likely to feel annoyed by the turbine noise than those who do not derive such a benefit.

3.2.3. Possibilities of the masking of the wind turbine noise

Earlier work on other sources of noise such as emanating for or industry had also revealed that those who benefit from the sources have high level of acceptance of the noise [170,171]. Also, visibility from the home (e.g., living room, bedroom) has been reported earlier, too, to affect annoyance from stationary sources [171].

Attempts have been made to see whether location of turbines in areas of pre-existing high background noise will face less opposition due to the masking of the turbine noise by the other background noise. In a study based in the Netherlands, Pedersen et al. [195] found that the presence of road traffic sound did not in general decrease annoyance with wind turbine noise, except when levels of wind turbine noise were moderate 35–40 dB(A) and road traffic noise level exceeded that level by at least 20 dB(A).

The extent of masking of wind turbine noise by the wind-induced rustling of vegetation has been investigated by Bolin [39] and by sea waves by Appelqvist et al. [21]. The extent varies with time as high turbine sound levels can occur when vegetation or wave noise is low, either on a short time scale during wind gusts or on a longer time scale associated with changes in the vertical wind profile. Also, as stated above, wind turbine sound can be audibly amplitude modulated due to differences in wind speed over the area swept by the rotor blades [243] and such amplitude modulations in a sound are more easily detected by the human ear [81] than a constant sound. This makes turbine-based noise conspicuous even if its average decibel level is not very high. This is borne out by several studies which indicate that at equal noise exposure levels, the expected annoyance due to wind turbine noise might be higher than annoyance due to other environmental noise sources [191,194,244]. The annoyance also appears to be high in comparison to exposure–response relationships for stationary sources, suggesting that wind turbines should be treated as a new type of source.

3.2.4. Reasons behind the unusual poignancy of wind turbine noise

In a study aimed to derive exposure–response relationship between wind turbine noise and the expected fraction of annoyed receptors, Janssen et al. [115] also find that in comparison to other sources of noise, annoyance due to wind turbine noise is found at relatively low noise exposure levels. In the overlapping exposure range, the expected percentage of annoyed persons indoors by wind turbine noise is higher than that due to other stationary sources of industrial noise and also increases faster with increasing noise levels. Furthermore, the expected percentage of annoyed or highly annoyed persons due to wind turbine noise across the exposure range resembles the expected percentages due to each of the three modes of transportation noise at much higher exposure levels.

Janssen et al. [115] also note that besides noise exposure, other individual and situational factors are found to influence the level of annoyance. In the study of Janssen et al. [115] also it was seen, as recorded in previous reports mentioned above, that those who derive economic benefit from the use of wind turbines have much greater tolerance for the turbine noise than others. Those who are not directly benefited from the turbines feel enhanced annoyance by turbine noise if one or more turbines are visible to him/her from his/her home [192,245].

Another factor, according to Janssen et al. [115] that could possibly explain the disproportionately large annoyance caused by wind turbines is the manner in which wind turbine noise originates and travels. The noise is emitted from a level that is several heights above the receiver: for the present-day turbines it may be from levels 50 to 130 m over the ground. This yields an amplitude modulated sound, for example with an amplitude of 5 dB [246] and a modulation frequency of 0.5–1 Hz. Furthermore the SPLs are not constant but keep varying with the wind velocity, irregularly and unpredictably. Such amplitude modulated sound being easily perceived [81] become particularly conspicuous in otherwise quiet areas, where people do not expect to hear much background noise.

3.2.5. Impact on human health

But what about impact on the health and the well-being of the receptors? Community noise has the potential to be an environmental stressor, causing nuisance, decreased wellbeing, and possibly non-auditory adverse effects on health [194,226]. To what extent annoyance caused by the wind turbine noise can impact a person's health?

In a recent study, Bakker et al. [27] find that turbine sound exposure can be related to sleep disturbance and psychological distress among those who are annoyed by the sound. The authors conclude that people living in the vicinity of wind turbines are at risk of being annoyed by the noise, an adverse effect in itself, and noise annoyance in turn could have greater repercussions *vis a vis* sleep disturbance and psychological distress. Annoyance must mediate this response, as no direct effects of wind turbine noise on sleep disturbance or psychological stress has been demonstrated. In other words, residents who do not hear the sound, or do not feel disturbed, do not seem to be adversely affected. Bakker et al. [27] also find that the extent of exposure to the wind turbine SPLs appears to have a proportional impact on the level of annoyance of the receptors; more the exposure greater the annoyance. These findings have been reinforced by another recent study [196] which reveals that the odds of perceiving wind turbine noise as well as of being annoyed by it increases with increasing SPLs. A rural area increased the risk of perception and annoyance in comparison with a suburban area; and in a rural setting, complex ground (hilly or rocky terrain) increased the risk compared with flat ground. Annoyance was associated with both objective and subjective factors of wind turbine visibility, and was further associated with lowered sleep quality and negative emotions.

It can be said, all-in-all, that people who live close to wind turbines and do not benefit economically from the turbines are at risk to experience sleep disturbance and psychological distress due to the turbines. This risk increases with increasing levels of the turbine noise. Hence there is a need to take the characteristics of different settings into account when planning new wind farms so that adverse health effects associated with each setting can be avoided.

During the last two decades extensive research efforts have been vested to improve aerodynamic design of the wind turbine's blades. These efforts aim to increase the power output while reducing the blades' mechanical loads and the aerodynamic noise. But a success of the order of a mere 10% has been achieved in comparison to the noise that was generated by the wind turbines in the early eighties.

3.2.6. The portents

In essence the problem with wind turbines is not that they make great noise but, rather, is that in a large number of cases they make noise in areas which otherwise were much quieter. As cities expand and noise-free or low-noise habitations become increasingly harder to find, the intrusion of wind turbine noise in such locations will become an increasingly contentious issue.

3.3. Impact on wildlife, especially birds and bats

3.3.1. Early reports

Among the earliest reports of wind farms causing harm to wildlife, especially avifauna, are the ones that came from Altamont Pass, California [110,183] and at Tarefa and Navarre in Spain [32]. In all the three locations relatively rare and long-lived species of birds (hence the ones with low rates of reproduction and growth) were involved. For example Golden Eagle (*Aquila chrysaetos*) was the most worrisome casualty at Altamont Pass and the Griffon Vulture (*Gyps fulvus*) at Navarre. At Altamont, Golden Eagles run into turbines when they congregated to feed on abundant pray while at Navarre the wind turbines often came in the way of the birds when they had to fly through topographical bottlenecks (such as mountain passes).

3.3.2. Lacunae in the available information

Over the years several authors have tried to assess the extent of risk posed to birds and bats by wind turbines, and the possible ways to reduce or eliminate the risk ([22,32,44,54,65,70,71,76,131,141,162,167,209,216,222,224]). But, as almost always happens with environmental impact assessment, more and more previously hidden cross-connections and uncertainties are encountered as newer studies are done and the information is looked at with newer perspectives. In the matter of turbine-induced wildlife mortality, also, several such complexities are coming into view:

1. Much of the past data on bird/bat deaths by wind turbines has not been corrected for scavenger removal [70,79]. Given that scavenger removal can occur within a few minutes to just a couple of hours of the bird/bat death, this induces a substantial extent of underestimation of the risk [158].
2. Possibilities also exist on missing of death counts even before scavenger removal because of large areas encompassed by several wind farms [190].
3. Wildlife is not jeopardized by wind turbines only by way of direct hits. There is also habitat destruction, reduction in breeding success, shifting of the predator–prey equations which, all, can adversely affect wildlife due to wind power development [50,59,158,185,213,249].
4. Data such as number of birds/bats killed per turbine masks as much pertinent information as it reveals. Firstly all turbines do not kill flying animals evenly and in a wind farm, substantial hits may be occurring in certain pockets which few or none in other pockets [84,165]. Secondly the species involved may be as —or more—important than the total number suffering the hit [44,216]. Rare species, endangered species, and species with relatively longer life spans and low rates of reproduction will suffer much more than other species [49,70,71,89,213].

Overall, the factors that may influence collision risks are related to

(a) turbine size, blade and hub design, and blade speed;
(b) number and the positioning of turbines in a wind farm;
(c) topography;
(d) weather;
(e) abundance of flying animals;
(f) species of the flying animals, hence flight altitude, flying speed, maneuverability, time spent in flight, and extent of habitat specialization;
(g) lighting.

3.3.3. Available pointers

The available information does reveal with fair certainty that the absolute numbers of turbine-killed birds and bats vary greatly among sites and that turbine collision risk of birds depends on a large number of factors, including bird species, numbers and behavior, weather conditions, topography, and the location size and the positioning of the wind turbines [90,139]. The risk is greater on or near areas regularly used by large numbers of feeding or roosting birds, or on migratory flyways or local flight paths. Large birds with poor maneuverability (such as swans and geese) are generally at greater risk of collision with structures [41,89] and species that habitually fly at dawn and dusk or at night are less likely to detect and avoid turbines [70,71,211,148]. Collision risk may also vary for a particular species, depending on age, behavior and stage of annual cycle. For example, work on terns by Henderson et al. [103] has shown that birds making frequent flights to forage for foods for their chicks are more susceptible to collision with overhead wires because they tend to fly closer to the structures lying in the path between foregoing sites and their nests.

More birds collide with structures when visibility is poor due to fog or rain [77,119,211]. Strong headwinds also affect collision rates and migrating birds in particular tend to fly lower when flying into the wind [204,265]. Collision risk in coastal and offshore areas is also likely to vary as birds move around in response to the state of tide and offshore currents.

As stated earlier, when rare, endangered, and slow-to-reproduce birds are involved, the impact of turbines can be decisive particularly in situations where cumulative mortality takes place as a result of multiple installations [70,71]. Some of the wind farms have caused enough deaths to have at least a local population-level effect on raptors [32,33,223,228,234] and seabirds [80]. The displacement of birds away from turbines can result in individuals abandoning otherwise suitable habitat, generally over distances of 100–200 m. These effects vary between sites, and species and season/stage of the annual cycle [68,108,109,136,147,149,189]. Garvin et al. [92] have shown that raptor abundance was reduced by 47% in Wisconsin, USA, after the construction of wind turbines in the study area than turbine kills. This reduction was more likely due to the abandonment of raptors from the wind farm project area. In a before–after impact study, Dahl et al. [59] have demonstrated that breeding success in territories of white-tailed eagles (*Haliaeetus albicilla*) adjacent to wind turbines can decline compared to before their construction resulting in a decline of the population growth. Carrete et al. [49] have shown that even a few turbine-killed Egyptian vultures (*Neophron percnopterus*) negatively affected the population growth of that species in Spain. Their study reinforces the premise that long-lived species are very sensitive to an increase in mortality, even if the increase is small [210]. Hence conclusions of low-impact drawn from some studies cannot be extrapolated to other locations and detailed site-specific assessments are necessary. For example a study on a 62-turbine wind farm in New Zealand by Bull et al. [44] showed that mortality occurred in 17 taxa but no bird of prey was killed. This information indicates that substantial shift in avian community structure was likely due to shifts

in predator/prey balances but such impacts are not quantified by mortality data.

Birds may get seriously injured or perish not only due to collisions with rotors, but also with towers, nacelles and other structures associated with wind farms such as guy cables, power lines and meteorological masts. Birds may also be forced to the ground as a result of being drawn into the vortex created by moving rotors [265].

If wind turbines are installed in topographies where birds have to funnel through confined spaces, significant risk of bird hits may arise. In some other situations, for example when following the coastline or crossing a ridge, birds lower their flight height [14,204]; this enhances their risk of collision with rotors [70].

3.3.4. Counter arguments that adverse impact is insignificant

Several forms of rebuttals exist to the claims that wind farms constitute a serious threat to avifauna. These include the following [168,211]:

- A much larger number of birds are killed by predators, poachers, and aeroplanes then by wind farms.
- In time birds develop the ability to 'sense' wind farms and avoid them
- Thermal power plants cause much bigger harm to wildlife habitat in general and birds in particular than wind farms do

None of the above arguments are false. But each masks the reality that even though wind farms are lesser evils than some other anthropogenic activities, the threat they pose is not insignificant. Even bigger reality these arguments mask is that the present extent of deployment of wind energy is very little compared to the scale at which it is planned to be used. The hub heights and blade lengths of the turbines are set to increase in future (Fig. 4) which would proportionately entrance the risk of damage to flying vertebrates. The sites that are 'ideal' in respect of high wind energy potential on one hand, and low adverse impacts on the other (for example minimum public opposition *vis a vis* visual intrusion and noise, harm to wildlife, etc,) are not easy to find. Hence the world will have to use less-than-ideal sites which will enhance the magnitude of the adverse impacts.

As for the ability of birds/bats to 'sense' wind farms and avoid them, there are several associated complications. The animals will have to spend greater energy to fly farther in their attempt at avoiding a large array of turbines. It will have the potential of disrupting linkages between distant feeding, roosting, molting and breeding areas otherwise unaffected by the wind farm [70]. The effect would depend on species, type of bird movement, flight height, distance to turbines, the layout and operational status of the turbines, time of day, wind force and direction, etc. The magnitude of impact will also be highly variable ranging from a slight diversion in flight direction, height or speed, through to significant diversions which may reduce the numbers of birds using areas beyond the wind farm. Moreover, a wind farm can effectively block a regularly used flight line between nesting and foraging areas. When there are several wind farms, which is how it will be when wind-based power generation attains its expected contribution of 20%, they will cumulatively create an extensive barrier which could force the birds/bats to take diversions of many tens of kilometers, thereby incurring substantial energy costs which may have knock-on impacts.

3.3.5. The emerging evidence

Even at the present, and much lesser than planned, level of utilization of wind turbines, evidence of their adverse impact on birds and bats is piling up. Pearce-Higgins et al. [190] collated bird population records of wind farms located on unenclosed upland habitats in the UK to test whether wind farm construction impacted breeding densities more or the wind farm operation. From the available data for 10 species, they found that red grouse (*Lagopus lagopus scoticus*), snipe (*Gallinago gallinago*) and curlew (*Numenius arquata*) densities all declined on wind farms during construction. Red grouse densities recovered after construction, but snipe and curlew densities did not. Post-construction curlew densities on wind farms were also significantly lower than reference sites. Conversely, densities of skylark *Alauda arvensis* and stonechat *Saxicola torquata* increased on wind farms during construction, indicating that the construction-induced disturbance was causing a shift in the avian community structure. The authors [190] note that the majority of onshore wind farm proposals in the UK have been in upland areas due to the high wind speeds occurring there and their isolation from centers of human population [203]. But these areas also happen to support avifauna of high conservation importance [188]. Wind farm-developments may result in significant reductions in habitat usage by the birds to the extent of radial distances 100–800 m away from the turbines after construction (depending on the species). This could result in reductions in the abundance of some breeding birds by up to 50% within 500 m of the turbines [189].

Studies have indicated that increased human activity in and around wind farms can influence the use of nest sites, foraging sites and flight paths of the avia [71] as well as displace them into suboptimal habitats reducing their chances of survival and reproduction [59,88,158]. So far few, if any, conclusive studies have been carried out on the relevance of such factors, which is mostly due to lack of BACI (before–after–control–impact), assessments [70,138]. Of particular concern is the fact that raptors in general occur at low breeding densities [181], and absence of BACI studies makes it impossible to judge the extent to which wind farms may be impacting them [59]. These species generally mature late, lay few eggs and have a long life span, making their population growth rate especially sensitive to changes in adult mortality [210], as well as loss of prey [158].

3.3.6. Trans-continental impacts

It has been conjectured since long [117,140] that when turbines kill migrating birds and bats, the reverberations of the impact may be reaching far and wide, crossing even continental boundaries. Now evidence has come from a recent study, in which Voigt et al. [249] have assessed the geographic provenance of bats killed in summer and autumn at German wind turbines on the basis of stable hydrogen isotopes in fur. They found that among the species killed *Pipistrellus nathusii* originated from Estonia or Russia, and *Pipistrellus pipistrellus* from more local populations. Noctule bats (*Nyctalus noctula*) and Leisler's bats (*Nyctalus leisleri*) were of Scandinavian or northeastern origin. Obviously wind turbines kill bats not only of sedentary local populations but also of distant populations, thus causing declines in bat populations on a large geographical scale. Voigt et al. [249] suggest that international regulations should be set up for implementing mitigation measures to prevent such large-scale detrimental effects of wind turbines on endangered bat populations.

3.3.7. Need for studies on effected populations

A major reason for the inadequacy and uncertainty in our understanding of the impact of turbines on birds is that complete population and not just individuals living in the close vicinity of turbines need to be monitored before and after the installation of a wind power plant. Only when such studies are conducted, useful knowledge about the impact of wind turbines on population growth rates of potentially affected species will accrue because

the ultimate measure of the impact of any action on a community of animals is the growth rate of their population [141,166,213]. A few years back Drewitt and Langston [70] had pointed out that further research to develop spatial and demographic models is needed which can help predict effects of individual wind farms and groups of developments which have cumulative effects across extensive areas. But such studies are still to be conducted.

Simulation modeling by Schaub [213] have revealed clear effects of both the number of wind turbines and their spatial configuration on the growth of a red kite population: the larger the number of wind turbines and the more they were spread out in a landscape, the more depressed the population growth rate became. Bird species having larger home ranges were seen to be much more negatively impacted by an increasing number of wind turbine locations than species with small home ranges.

Simulations by Schaub [213] also show that an enhancement of the collision risk from 0.5 to 0.8 would have a strong negative effect on population growth, thereby indicating that the potential of wind turbines to harm avifauna cannot be underestimated.

3.3.8. The proposed strategies to prevent or reduce harm to birds and bats

As of now the usual assurances that are given when promoting any and every developmental activity that threatens to harm the environment, are given for new wind farms as well, viz “the activity will not adversely affect the environment if planned and implemented with proper environmental safeguards.”

In case of the impact of wind energy on wildlife, the safeguards that have been proposed are

- A wind park should be so designed as to eliminate the probability of harming the natural environment significantly, especially birds. All possible impacts on birds and other wildlife should be considered beforehand.
- Systematic pre-construction studies and post-construction forecasts should be made to explore the potential impacts of wind parks on wildlife and determine wind farm siting in a way that optimizes electricity production while maximizing conservation of wildlife.
- Necessary measures for the protection of birds must be introduced during the wind park's construction and operation.
- Collaboration should be fostered between the wind farms' developers, the relevant governmental agencies, and laypersons to ensure proper siting, construction, operation, and maintenance of wind farms.

As with all other activities, for wind farms also ‘longer-term’ impact assessment studies are advocated with extensive data collection and proper follow up on its basis to ensure that little or no adverse impacts are caused.

It is possible to draw a long list of ‘dos’ and ‘don'ts’, of best practice measures, with which harm to birds, bats and other wildlife from wind power projects can be minimized. For example

(i) ensuring that key areas of conservation importance and sensitivity are avoided;
(ii) conducting systematic ‘before’, and ‘during’ surveys to assess adverse impacts and minimize them;
(iii) ensuring appropriate working practices and restoration measures to protect sensitive habitats;
(iv) providing adequate briefing for site personnel and, in particularly sensitive locations, employing an on-site ecologist during construction;
(v) ensuring a vigorous post-development monitoring program by stipulating it as a pre-requisite for licensing the wind farm;
(vi) siting turbines close together to minimize the development footprint (subject to technical constraints such as the need for greater separation between larger turbines);
(vii) grouping turbines to avoid alignments that are perpendicular to main flight paths of the avia and to provide corridors between clusters, aligned with main flight trajectories, within large wind farms;
(viii) increasing the visibility of rotor blades to the extent it is compatible with the landscape, and using UV paint, which may enhance the visibility of rotor blades to birds;
(ix) installing transmission cables underground, wherever possible;
(x) marking overhead cables using deflectors and avoiding use over areas of high bird concentrations, especially for species vulnerable to collision;
(xi) timing construction to avoid sensitive periods;
(xii) implementing habitat enhancement for species using the site;
(xiii) carefully timing and routing maintenance trips to reduce disturbance from boats, helicopters and personnel (in case of off-shore turbines);
(xiv) fostering collaboration between the wind farm developers, relevant government agencies and people living close to the farms to ensure proper siting, construction, operation, and maintenance of the farms according to agreed ‘best practice codes’.

It can be added that extensive BACI studies on avifauna at local as well as regional levels should be made mandatory to ensure that any possible harm to the birds during construction is minimized while any adverse post-construction impact, if detected, may be ameliorated. Risk assessment frameworks as proposed by Garthe and Hüppop [90], and refined by Christel et al. [54], Furness et al. [89], Seaton and Barea [216], De Lucas et al. [65] and others can be helpful in quantifying BACI. Techniques and methodologies introduced earlier to assess risk of accidents can also be made a basis for developing BACI assessment tools [122–130,273].

3.3.9. The portents

For any and every developmental activity, it is possible to say, “the adverse impacts will be minimal if ‘best practice’ is adopted.” In turn the ‘best-practice’ comprises of the kind of actions listed above which not only need input of state-of-the-art technology, but commitment on the part of all stakeholders and a great deal of investment. But investments in environmental protection reduces the short-term profitability of any venture and there is a general tendency to keep such investments to a minimum. Even governments bypass their commitments towards environmental safeguards in their anxiety to make energy projects ‘profitable’ [5,8]. So many violations of environmental concerns are occurring, so commonly and at such a large scale that ‘best practice’ recommendations are followed in breach rather than in compliance. To what extent wind farm developers across the world will like to invest money in protecting birds and bats? Wisdom of hindsight tells us that the plausible answer is ‘not much’.

Another major difficulty with the ‘best practice’ paradigm is that what we call best practice at any point of time is dependent on the extent of our grasp of the situation at that point of time. Until two decades ago best practice for thermal power projects *vis a vis* gaseous emissions meant control of SOx and NOx. Control of CO_2 was not a concern at all. Likewise, till very recently no set of best practice guidelines for hydropower or geothermal projects carried any instructions to deal with methane or N_2O emissions. As the number of wind forms go up, and as other developmental pressures add to the threat being faced by wildlife, the measures

that appear adequate today may prove ineffective in the near future.

Yet another problem is that best practice is a contextual phenomenon: what is best practice for a city, state, or country is not necessarily a best practice for another city, state, or country. Given this reality, even national consensus on best practice is difficult to arrive and what is agreed upon gets deviated here and there due to compulsions of accommodating conflicting interests. The prospect of achieving global consensus and commitment on truly best practice appears remote.

If best practice is difficult to specify it is very difficult to legislate, and, on the ground, almost impossible to enforce. In India, for example, very elaborate and strict norms for best practice exist for all kinds of developmental activities. Technology, manpower, and other resources to implement the best practice are also available. No industry, power project, or any other developmental activity is allowed without elaborate EIA and written commitments that best practice shall be followed. Despite all this, numerous factors operate to cause major deviations from best practice. There are governmental agencies and nongovernmental watchdog groups to prevent this but even the task of randomly policing a statistically significant number of industries is so huge that across-the-board enforcement of best practice has been impossible.

3.4. Shadow flicker

Shadow flicker is a unique impact associated with only wind energy form among all other energy sources. When it occurs fleetingly, a flicker is totally benign and is barely noticed. But a persistent flicker can be as disconcerting as lights coming on and going off in a room in quick succession for several hours.

The blades of a wind turbine cast a shadow when sunlight or some other light from a strong source falls on them. If the blades happen to be rotating, a flicker is generated. Depending on the angle of the incident light and its intensity the flicker may cause feelings ranging from undesirable to unbearable [58,247].

On a clear day, and a little after the sunrise and a little before the sunset, the shadow of a 22 m turbine blade may be visible up to a distance of 4.8 km. The flicker of a 3 MW wind turbine, which has a blade of about 45 m length and 2 m width, may be visible up to a distance of 1.4 km in one or other direction for most part of the day. Weaker shadows may be cast up to a distance of 2 km from the turbine [120,247]. At dusk the flicker may distract drivers, heightening risk of accident [154].

Alongside the area of impact, which grows larger with taller turbines and longer blades, the relevant aspect is the flicker frequency. Indeed it is the flicker frequency which is the principal cause of annoyance and should be kept at no more than three blade's passes per second, or 60 rpm for a three-bladed turbine. The flicker would be sharper if turbine blades are reflective. The strategy to reduce flicker by reducing blade speed acts against turbine efficiency.

In the course of a day, the shadow of a wind turbine moves as the sun rays change direction from east to west. Since the sun-path changes during the year, the route of a wind turbine's shadow also changes from season to season. It is a mixed blessing—the positive side is that any area suffers from a wind turbine's shadow flicker for only a specific duration in an year. The negative side is that overall a much larger area comes within the impact range of the flicker making the challenge of addressing this problem that much greater. In certain situations, for example in the island of Crete studied by Katsaprakakis [120], which has small mountainous settlements dispersed everywhere, impacts of wind turbine noise and flicker are impossible to avoid.

The only way to present flicker from causing annoyance is to locate wind farms well away from where people live. This adds yet another difficulty to the problem of finding sites for locating wind farms.

3.5. Electromagnetic interference

The possible ways in which wind turbines can cause electromagnetic interference are [35,99]

- distorting the transmissions of existing radio or television stations;
- generating their own electromagnetic radiation.

Transmission signals from radio or television (especially of FM broadcast frequencies) can get distorted when passing through the moving blades of wind turbines. This effect was more pronounced with the first generation wind turbines which had metallic blades. The present day wind turbines are exclusively made of synthetic materials which have much milder impact on the transmission of electromagnetic radiation [227,261]. The flip side is that a very large number of telecommunication towers now exist everywhere which were not there during the first generation wind turbine era. Hence the number of people likely to be impacted has grown enormously. In some of the countries license for a wind park is granted only if certain prescribed minimum distances are kept from telecommunications or radio and television stations. This places yet one more hindrance in the path of the siting of wind farms. Installation of additional transmitter masts can alleviate the problem but at a cost.

As far as the generation of electromagnetic radiation by wind turbines is concerned, the parts of a wind turbine which may contribute are the electric generator and the voltage transformer. The electromagnetic fields these parts generate are weak and are confined to within a short distance from the turbine housing [43,217]. They nevertheless add to the already increasing background electromagnetic radiations (EMRs) load caused by telecommunication towers. They also add to the exposure of humans to EMR which has dramatically increased in recent years due to cell phone use [202] and which is being implicated with the risk of cancer, among other health risks.

3.6. Land requirement

Proponents of wind energy argue that wind farms do not actually occupy as large land areas as appears from a cursory glance. A 3 MW wind turbine needs about a 40 m × 40 m chunk of land, or a 1600 m^2 square, outside which agriculture or any other land-use activity can go on unhindered [120]. This is true, too, for certain types of land-uses such as for pasture or horticulture. But when the number of wind farms increase dramatically to meet the kind of targets that have been advanced by the IPCC [113] it would be increasingly difficult to find large areas to locate wind farms without coming into serious conflict with the existing land-use. Moreover recent findings as detailed in the following section indicate that wind turbines can enhance water loss and require greater expenses than would otherwise incurred in irrigation. They also raise temperatures downwind which may have difficult-to-forecast impacts on agricultural production, of which at least some can be unfavorable.

3.7. Climate change

Due to the temperature differences that are generated at planetary scales by the non-uniform heating of the earth by the sun, winds of different speeds are created throughout the atmosphere. The turbulent mixing caused by these winds in the upper atmosphere transports momentum downward towards the earth's

surface. The average downward flux of kinetic energy in this manner over the global land surface is about 1.5 W m^{-2}. It is small in magnitude but influences much larger energy fluxes by the heat and moisture that the winds transport. Parts of this flux are extracted by wind-turbine arrays [42]. In absolute terms the magnitude of power thus extracted is a miniscule fraction of the power carried by winds across the globe, but in the context of near-surface hydrometeorology the proportion extracted is significant enough to cause major perturbations, as explained below.

When wind masses move across the blades of a wind turbine, a sizeable fraction of the wind's momentum is transferred on to the turbine which converts it into electrical energy. The yearly average flux of kinetic energy that passes through a tall and large wind turbine is of the order of 1 kW m^{-2}. Significant fractions of it are transformed into electrical energy by the turbine and the exiting wind has that much less momentum. These happenings in the wake of each turbine have the effect of disturbing the natural exchanges of energy between the land surface and the atmospheric layers close to it. This may alter the local hydrometeorology and may have a cascading effect on atmospheric dynamics.

Two groups of scientists—Baidya Roy et al. [26] and Keith et al. [121], working independent of each other—were the first to suggest that utilization of wind for power generation on a large scale may influence the global climate. The report of Baidya Roy et al. [26] was based on the premise that even though the rate at which wind farms extract energy from the atmosphere is miniscule in comparison to the kinetic and potential energy stored in the atmosphere, it is highly significant in time-tendency terms—for example rate of conversion of energy from one form to another, frictional dissipation rate, etc. Parallely, and independently, Keith et al. [121] expressed the same possibility, Keith et al. also suggested that alternation of the wind-based kinetic energy fluxes in the course of power extraction by wind turbines can have much stronger influence on the climate than alternation in radiative fluxes of identical magnitude. This is because of the wind's role, mentioned above, in mediating much larger energy fluxes by transporting heat and moisture.

Both groups had based their theories on the modeling of hypothetical wind forms. Their reports have, expectedly, generated a debate which continues to rage in much the same way it had happened *vis a vis* global warming [10]: for a long time more people believed that global warming was the figment of imagination of a few paranoid scientists and was, at worst, a very distant possibility. A number of calculations were advanced to show that either there is no significant warming or, if there is some, it is of no net harm. Indeed for some years during the 1970s and early 1980s it was global *cooling* that was forecast and feared by a section of scientists [61,173,232]. In case of the effect of wind turbine operation on climate, also, reports based on theoretical studies have appeared which suggest that the impact will be insignificant [225]. But concrete evidence is beginning to emerge that wind farms do impact the local climate.

On the basis of an analysis of satellite data for the period of 2003–2011 over a region in west-central Texas, where four of the world's largest wind farms are located, Zhou et al. [267] have found a significant warming trend of up to 0.72 °C per decade, particularly at night-time, over wind farms relative to nearby non-wind-farm regions. The authors have been able to link this warming to the impact of wind farms because the spatial pattern and magnitude of the warming has coupled very well with the geographic distribution of wind turbines.

The findings of Zhou et al. [267] have been corroborated by an independent study on San Gorogonio Pass Wind Farm situated in southern California, by Walsh-Thomas et al. [254]. These authors have found that downwind regions, south and east of the wind farms are typically warmer than those west of the wind farm. The extent of downwind warming varied from 4 to 8 °C. A typical pattern of downwind rise in ambient temperature as observed by Walsh-Thomas et al. [254] is presented in Figure 5.

Theoretical studies are also piling up which forecast significant impact on climate of wind turbines. It has been shown [12] that large wind farms directly influence the atmospheric boundary layer by (a) reducing wind speeds, (b) generating blade scale turbulence in the wake of the turbines, and (c) generating shear driven turbulence due to the reduced wind speeds in the turbine wake. Large wind turbines can also have indirect effects on the local climate by influencing surface roughness, advection of heat and moisture, and turbulent transport in the boundary layer [132].

Wang and Prinn [255] have used a three-dimensional climate model to simulate the potential climate effects associated with installation of wind-powered generators over large areas of land or coastal ocean. It is seen that using wind turbines to meet 10% or more of global energy demand (as has been proposed by the IPCC [113]), could cause surface warming exceeding 10 °C over land installations. The model forecasts that impacts resulting in significant warming or cooling can occur even in places remote from wind farms. Alterations of the global distributions of rainfall and clouds can also occur. The impacts have their origin in the competing effects of increases in roughness and decreases in wind speed on near-surface turbulent heat fluxes, the differing nature of land and ocean surface friction, and the dimensions of the installations parallel and perpendicular to the prevailing winds.

3.7.1. Suggested measures and their limitations

Baidya Roy and Traiteur [208] have explored the possibility of low-impact wind farms to minimize the impacts on surface temperature. One option to achieve it, according to the authors, is to design roters that generate less turbulence in their wakes, thereby lessening the downstream impacts on the local climate. The other option is to locate wind farms in areas where background atmospheric boundary layer (ABL) turbulence is high due to natural reasons.

Of these, the engineering solution is expensive because it involves designing new rotors. The siting solution is convenient in terms of its reliance on currently available technology, but it requires wind farms to be sited in regions with high background ABL turbulence. Firstly, prolonged exposure to such turbulence may be damaging to the rotors, and, secondly, it may put wind farms away from the points of use of their power, enhancing transmission costs and losses. There are also suggestions that the extent of wind energy extractable across the world is about half of what has been estimated is the past [13].

It is often said in support of wind farms that they can be put up over agricultural land, thereby enhancing land-use without major disturbance in the existing land-use. Such siting can also help farmers in supplementing their income with rent from utility companies. But impacts from wind farms on surface meteorological conditions such as enhancing water loss from soils due to higher rate of evaporations, are likely to affect agricultural practices in these farms [271,272]. One of the direct consequences may be the necessity to spend more money on irrigating the affected area [215]. If the wind farms are sufficiently large, they may affect downstream surface meteorology a long way. As wind farms become larger and more ubiquitous, such impacts may multiply.

4. Environmental impact of offshore wind farms

Whereas onshore deployment of wind energy for generating electrical power has a history going back to the 1880s, the first offshore wind turbine was installed only a few decades ago—in 1991 [46]. As a result, the world has had much lesser time to

experience the adverse impacts of offshore wind farms (OWFs) in comparison to inland wind farms (INFs) but some advantages of the former have appeared obvious. If an OWF can be installed so far off in the sea from the coast that it goes out of sight of beach-farers, the problems of adverse visual impact, noise-related trauma to humans, image flicker, and electromagnetic interference can be largely avoided. Concerns of real-estate value of land and the prospect of the value getting jeopardized by wind turbines also do not operate in case of OWFs. Hence the biggest hurdle in the path of wind energy development—public opposition on account of the NYMBI syndrome—may be largely bypassed. These perceived advantages on one hand, and the pressures to reduce the contribution of fossil-fuels to the energy mix on the other, has prompted great efforts to take wind-based power generation offshore. Indeed the quantum of envisaged OWF-based electricity generation is so high that, if implemented, it would dwarf the INF-based initiatives.

But, by all indications, even as OWF may take some of the old problems out of sight, hence out of mind, they may generate massive new problems of their own. Marine environments are already under severe stress due to overfishing [40], pollution [53,251], ozone hole-related UV-B exposure [60,99,197]), and ocean acidification [8,133,169]). Installation of large wind farms will jeopardize the marine environment still further. Of particularly serious concern is the situation in countries like Scotland who wish to simultaneously exploit marine wind, wave, and tidal energy sources, each on large scale [73]. As practically nothing is known about the cumulative impacts of such development, it amounts to a very risky leap into the unknown. Impacts of OWF encompass [73]:

- Acute noise-related impacts during construction phase, especially due to driving, drilling and dredging operations.
- Disturbance due to intensive marine and aerial transportation activities during exploration, construction and maintenance.
- Generation of polluted sediments during construction and their re-suspension.
- Collisions of birds and other organisms with OWF structures.
- Creating of the artificial reef effect by the presence of structures, individually and in arrays, with concomitant impacts on biodiversity.
- Chronic, long-term, impacts due to continual operational noise and vibrations emanating from OWF.
- Electromagnetic impacts arising from underwater cable networks that may interfere with animal navigation.
- Thermal impacts that may aggravate the impacts of other stressors on the benthos.
- Impacts of episodic traffic increase for trouble-shooting.
- Impacts during physical decommissioning, particularly the steps which would involve the use of explosives.

Among the adverse impacts of OWF are those that are common to IWF: collision risk to birds and bats [22,25], noise, and electromagnetic interference (EMI). The difference is that the last two impacts will not harm us directly as IFWs do, but shall harm us indirectly by adversely effecting marine ecosystem. In addition OWF pose significant risk to marine invertebrates, fish, and mammals due to habitat fragmentation, noise, vibrations, electromagnetic interference, etc., just as IWFs pose a risk to land-based wildlife [158].

4.1. Impact of anchorage, or the ‘artificial reef effect’

There have been reports that the anchorage off-shore platforms provide to invertebrates and fish may be beneficial for their growth. For example oil platforms and piers are known to attract marine organisms [102,157]. There are even reports that the density and biomass of fish in some of the artificial habitat created by man-made structures was found to be higher in comparison to the surrounding areas and even local natural reefs [258,260]. But the species composition in such ‘artificial reefs’ is vastly different from that of the natural reefs and may impact the biodiversity of surrounding areas [56,112,205]). Such structures are also known to promote the establishment and spread of alien species and harmful algal blooms [45,187,248]. Moreover the perception of enriching fisheries may be illusory as it may arise due to migration from surrounding areas and, thus, may be occurring at the expense of previously unexploited stock [95]. According to an estimate of [262], the net amount of monopole exposer per offshore turbine creates 2.5 times the amount of area lost to placement of monopole on the sea bed.

‘Floating’ wind turbines, which are anchored to the sea bed but are free to move on the surface, have extensive moorings and are known to facilitate aggregation of fish [82,250,259]. But, again, it is not clear whether these devices increase recruitment or merely attract fish from nearby areas [52,112]–if the latter occurs the devices would be a means of over exploitation, hence net decline rather than promotion of fisheries.

As for benthos, the artificial reef effect will benefit some species but may negatively affect others [145]. Structural elements placed in sand bottoms may result in greater benthic diversity [116], but this may also affect adjacent communities through greater predation [146]. All-in-all OWFs are expected to change faunal community from those associated with sand/gravel habitat to those who use reefs [163]. Shifts in floral communities would also occur [153].

4.2. Collision risk

There is even much less information and much greater uncertainty associated with collision risk posed to birds and bats by OWFs than is the case with IWFs. As happens at IWFs, birds may show two kinds of avoidance behavior at OWFs which can be termed as ‘macro-avoidance’ and ‘micro-avoidance’. The former occurs when birds alter their flight path to keep clear of the entire wind farm [67], whereas the latter occurs when birds enter the wind farm but take evasive action to avoid individual turbines [31,55]. Unless species-specific rates of macro- and micro-avoidance are known, it is not possible to assess vulnerability of different species or the overall population. But such data is lacking and what little is available, is fraught with uncertainty 55,89]. Since most carcasses are usually not found in OWF areas, it is even more difficult to ascertain OWF-related bird mortality than is IWF-related bird mortality.

What can be said with certainty is that large number of factors can heighten collision risk of birds at OWFs. These include characteristics of turbines and geometry of arrays formed by the turbines, weather conditions, topography, bird species, and numbers of birds using the site. Species-specific risks are a function of flight altitude, flight maneuverability, percentage of time spent in flying, nocturnal behavior, and habitat specialization [89,90,214]. Wind farms located along the migratory routes or in habitats frequented by birds would carry greater collision risk. Turbines constructed linearly in long strings may cause more avian collisions than turbines that are constructed in clusters. The heights, blade lengths, tip speeds, blade appearance to birds, and presence and type of lighting are other factors that determine the collision probability. Turbines featuring taller towers and larger blade lengths with slower tip speeds pose greater collision risks to flying animals [175]. Species abundance at wind farms may also influence collision risks because collision rates at some wind farms are higher for those species that are the most abundant.

Although migrating birds generally fly at altitudes higher than 150 m, they descend to lower altitudes during high winds, low clouds, and rain. This increases the probability of them hitting the wind turbines.

As OWFs carry navigation lights, which have the potential to attract seabirds, there is additional risk of collision due to the lights [176]. The few studies that have been done so far suggest that impacts are highly dependent on the site in terms of conservation importance of the impacted species as well as physical factors that influence the probability of a hit ([70,87,90,159,229]. In general OWF may have a negative impact on local bird abundance [229]. Moreover indirect impacts on avifauna can occur as OWFs can disrupt or remove feeding and/or breeding habitats.

As for collision risk between submarine animals and OWF, virtually nothing is known [263] have conjectured that fixed submerged structures are likely to pose little collision risk, but cables, chain, power lines and components free-moving on the surface or in the water column may pose a much higher risk of collision. A variety of marine organisms are attracted to marine light sources of the type present on OWF [100,164] which may heighten collision risk.

4.3. Noise

There is an increasing body of evidence that noise has the adverse effect over a range of aquatic organisms, especially vertebrates [74,107]. OWF will be a source of significant extra noise, not only during the construction phase but during operation as well, and may impact marine life due to it [57,63,179,180,235] Acoustically sensitive species such as marine mammals are likely to be particularly vulnerable as pile-driving has been observed to directly affect the behavior of seals [75] and cetaceans [51,104,238]. For example, [51] found that harbor porpoises appeared to leave the construction area of an offshore wind farm after pile driving (which produces sound in excess of 205 dB) commenced. In the marine environment, hearing is a much more important sensory input than vision, and cetaceans, in particular, have highly-developed acoustic sensory systems with which they communicate, navigate, forage and avoid predators [73]. Fish can also detect pile-driving noise over large distances, which may affect intra-specific communication, or may dampen their ability to perceive lesser sounds, making them lose orientation or make them more vulnerable to predation [200,235]).

Noise during the operational phase is likely to be less poignant and its significance my lie in terms of chronic, long term effects. [135] examined the response of porpoises (*Phocoena phocoena*) and seals (*Phoca vitulina*) to simulated 2 MW wind power generator noise, and found that the seals surfaced at greater distances from the sound source compared to distances without noise. Similarly, approach distance to porpoises increased when the simulated generator noise was turned on. By an estimate ([235]) the operational noise of wind turbines will be audible to *P. phocoena* positioned 100 m away, and to *P. vitulina* over 1 km away. Fish may not get traumatized by OWF noise but the noise may mask their communication and orientation signals [20,252].

Little is known with which to conjecture as to how other marine animals will react to OWF noise. Sea turtles have been shown to suffer stress from anthropogenic noise [212], but no *in situ* studies exist [163]. A recent study [199] has shown that simulated wind turbine noise significantly increased the median time to metamorphosis for the megalopae of crabs *Austrohalice crassa* and *Hemigrapsus crenulatus.*

Based on an assessment of the state-of-the-art, [221] aver that OWF pose a significant risk to whales, dolphins and porpoises, even as proponents of OWF have been hoping that possible benefits (e.g., artificial reef creation) may take precedence over the negative impacts if–and it is always a very big 'if'–mitigation strategies are effectively implemented [198].

4.4. Electromagnetic interference and temperature rise

OWFs depend on intensive network of electrical cables to transfer power between devices, to transformers and to the mainland. The resulting electromagnetic fields (EMFs) will be of similar strength to that of the Earth in close proximity to the cables [253], and so have the potential to affect magnetosensitive species such as bony fish, elasmobranchs, marine mammals and sea turtles [96,160,264]. EMFs could also affect animals which use geomagnetic cues during migration [155].

For example eels have been seen to respond to EMFs by diverting from their migration route [256]. Benthic elasmobranchs also respond to EMFs emitted by subsea cables. As for direct impact of EMF on animal health, little is known with certainty as of now. As brought out by Lovich and Ennen [158], perceptions of different assessors range from 'minor' [198,211]) to major [28–30]. It is suggested that chronic EMF exposure could impact nervous, cardiovascular, reproductive, and immune systems of impacted wildlife.

Moreover there are predictions that electricity production at OWF will increase the temperature in the surrounding sediment and water. Perhaps the thermal effect may be just a small rise in temperature within a few centimeters of the cable and may, by itself, be not a major stressor to benthic communities but in combination of other stressors might assume significance. The development, operation and decommissioning phases, of an OWF will span many decades and would be a hub of activity that will impact marine ecosystem in many ways–quite a few of which the nature and extent is unknown and quite a few not even foreseen as of now.

4.5. NIMBY

OWFs are much less affected by the NIMBY (not in my backyard) syndrome that besieges IWFs but are not entirely free from it [37,101,257]. Farther on OWF is located from the shore more costs and greater carbon footprint it entails by way of increased transportation and transmission costs. Closer to shore it is more visually intrusive it becomes. Particularly contentious are the issues relating to eco-tourism [257], and no broad consensus or formula exists on how to get around these issues. What is known with certainty is that OWFs cost 1.5–2 times more to install and 5–10 times more to maintain than IWFs of comparable capacities [261].

4.6. Vibration and flicker effects

Wind turbines produce infrasound that are below the audible range of humans but are potent enough to cause houses and other nearby structures to vibrate [2]. Several species of animals are able to perceive such low-frequency vibrations through their skin. It is this ability which enables several animals to 'foresee' earth quakes and tsunamis before the calamities actually strike them [47,94]. It is likely that vibrations caused by OWF may mislead some of the marine species and may mask vibration-related cues in some other.

Likewise the light flicker generated by wind turbines may be stressful to marine fauna but absolutely nothing is known about it.

5. Life cycle assessments

A large number of life cycle environmental impact assessments have been done of wind power and even several assessments or reviews are available of those assessments [19,23,64,72,85,98,137,152, 239,268]. Given that an LCA is [97] a "compilation and evaluation of

the inputs, outputs and potential environmental impact of a product system throughout the life cycle", the results of an LCA depend very strongly on what all is included, in what form, and with what weightage. A great deal of subjectivity becomes unavoidable [64], so does imprecision. As a consequence, despite hundreds of LCAs, already done, and new ones continuing to be reported [93,186,206] it is not possible to say with any certainty how much more beneficial to environment wind energy is in comparison to other sources of energy. For example the CO_2 emission intensities of wind power as arrived by different LCAs vary from 7.9 to 123.7 g/kWh of electricity generated [64]. Return on investment (ROI) results of 50 studies compiled by [137] range from 1.8 to 125.8! Larger turbines leave smaller ecological footprint per kW of power they generate [48,66], but have greater adverse impacts than smaller turbines have, in terms of visual disagreeability, collision risk to avifauna, impact on weather, etc.

Several factors contribute to the discrepancies between different LCAs: difference in scales of systems (such as large/small turbines), key assumptions (such as lifetime, capacity), basic data (such as emissions associated with constituent materials), and the type, range, and coverage of the LCA [19]. A lot, eventually, depends on what the author of the LCA hopes to highlight–the LCA, then, consciously or sub-consciously tends to acquire that orientation. It is generally agreed that OWFs use up more fossil fuels than IWFs because OWFs need more intense and regular transportation for their commissioning, operation and maintenance, and decommissioning, than IWFs do [206].

Reports have also appeared (e.g. [168]) which estimate harm to human health and environment caused by fossil fuels in monetary terms and show that we gain that much cost advantage from wind energy by way of the averted harm. But such estimates are based on a tacit assumption that wind energy would have no different or no greater total impacts when used to meet 20% or more of global energy demand than they are exerting at their present (and miniscule) level of utilization. There is no rationale behind such an assumption.

6. Summary and conclusion

Wind energy is the most extensively utilized of all renewable energy sources at present (if large hydropower is not considered as it usually is not), even as its contribution to the global energy production is a mere 0.2%. Now moves are afoot all over the world, especially in the USA, the EU, China and India, to substantially enhance the share of wind energy. The Inter-governmental Panel on Climate Change expects the world to meet 20% of its energy demand with wind energy by the year 2050. This means the world would need to generate 50 times as much power with the use of wind by 2050 as it is doing at present.

But even with the present levels of the use of wind turbines, adverse environmental impacts are increasingly coming to light. The paper summarizes the current understanding of these impacts and tries to assess how their magnitude is likely to increase with the increase in the deployment of wind turbines. It is seen that the adverse impacts are likely to be substantial and their impacts may increase in complexity and magnitude in proportion to the extent of use of wind as an energy source.

Among the major hurdles in the path of wind energy development so far has been the NYMBI (not in my backyard) syndrome due to which there is increasing emphasis on installing windfarms several kilometers offshore. But such moves have serious implications for the marine life which is already under great stress due to impacts of overfishing, marine pollution, global warming, ozone hole and ocean acidification. Evidence is also emerging that the adverse impacts of wind power plants on wildlife, especially birds and bats, are likely to be much greater than is reflected in the hitherto reported figures of individuals killed per turbine. Likewise recent findings on the impact of noise and flicker generated by the wind turbines indicate that these can have traumatic impacts on individuals who have certain predispositions. But the greatest of emerging concerns is the likely impact of large wind farms on the weather, and possibly the climate.

The central message of the review is not that wind energy is a greater evil than fossil fuels. It, rather, is that large scale replacement of fossil fuels with wind energy will not be as unmitigated a blessing as has been widely believed on the basis of generally small-scale and highly dispersed use of wind energy accomplished so far. The review also gives the message that a shift to renewables like wind energy may be beneficial only if it is accompanied by a reduction in the overall energy use.

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